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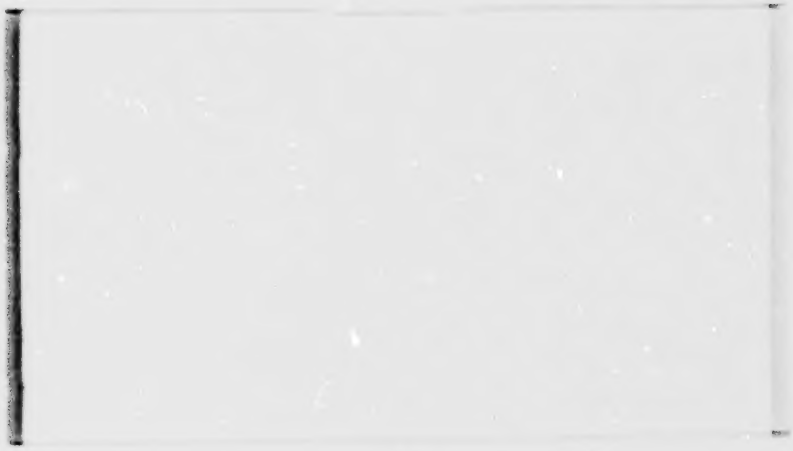

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THE EFFECT OF THERMAL ENVELOPE UPGRADING IN RESIDENTIAL DWELLINGS

Report No 87-55-K

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Utilization Engineer
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Abstract

Sixteen dual energy homes were thermally upgraded in various ways and their energy consumptions monitored for a year before and a year after the retrofit to determine the energy consumption and power demand reductions produced. The data were analyzed to eliminate the effect of weather and other random usage variations. Consumption savings averaged 6% and demand savings 13%, both with much individual variation. Predictions of the upgrading effect were calculated using the HOTCAN computer program. HOTCAN significantly overpredicted consumption and demand, both in absolute terms and as percentage reductions, with the standard house operation assumptions used. Airtightness fan tests, performed before and after upgrading, did not reliably indicate the effects of airsealing on natural air change rates. The work was inspected and revealed a few minor problems; lowered natural air change rates after retrofitting in a few cases required occupant adaptation (exhaust fans were installed in one house). Based on the upgrading costs expended and the resulting savings to the homeowner and the electric utility, there were modest net savings in most cases. As a result of this work, some general conclusions and recommendations for homeowners, energy advisors, electric utility retrofit programs and researchers are made.

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REPORT FOR THE

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REPORT No. 207 U 324
THE EFFECT OF THERMAL ENVELOPE UPGRADING IN RESIDENTIAL DWELLINGS
VOLUME I - MAIN REPORT AND APPENDIX A

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JULY 1986

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ABSTRACT

Sixteen dual energy houses were thermally upgraded in various ways and their energy consumptions monitored for a year before and a year after the retrofit to determine the energy consumption and power demand reductions produced. The data were analyzed to eliminate the effect of weather and other random usage variations. Consumption savings averaged 6% and demand savings 13%, both with much individual variation. Predictions of the upgrading effect were calculated using the HOTCAN computer program. HOTCAN significantly overpredicted consumption and demand, both in absolute terms and as percentage reductions, with the standard house operation assumptions used. Airtightness fan tests, performed before and after upgrading, did not reliably indicate the effects of airsealing on natural air change rates. The work was inspected and revealed a few minor problems; lowered natural air change rates after retrofitting in a few cases required occupant adaptation (exhaust fans were installed in one house). Based on the upgrading costs expended and the resulting savings to the homeowner and the electric utility, there were modest net savings in most cases. As a result of this work, some general conclusions and recommendations for homeowners, energy advisors, electric utility retrofit programs and researchers are made.

Keywords: Thermal envelope upgrading, energy retrofit, residential space heating conservation, consumption and demand savings, airsealing, insulation, airtightness tests.

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SUMMARY

Because a majority of the housing stock for the next several decades has already been built, thermal upgrading of existing dwellings deserves attention as an energy conservation measure. This report analyses reductions in heating energy and demand achievable by various upgrading measures.

A previous study, CEA RP 120 U 281, established a detailed history of the energy usage and demand characteristics (design heat losses) of 49 dual energy (oil/electric) houses . In the field trial reported here, the thermal envelopes of sixteen of these houses were upgraded in the fall of 1982. Continued monitoring for another heating season allowed direct measurement of the resulting energy and demand reductions. Also, inspection of the work and continuing scrutiny of the houses were meant to uncover any problems arising from the retrofits. Costs were noted and airtightness fan tests were done before and after upgrading. The best available predictive model was used to attempt to generalize the results obtained.

The houses were grouped into upgrading categories as follows: 3 homeowner airsealed (one of which had attic insulation added independent of this experiment), 4 contractor airsealed, 4 contractor airsealed and basement wall insulated, 3 contractor and one homeowner basement wall insulated, and one contractor attic insulated. The houses, roughly typical of Ontario dwellings, are spread geographically and climatically throughout the province.

Individual upgrading costs ranged from $110 (homeowner airseal) to $4300 (contractor airseal and basement insulation). Inspection of the work and subsequent questionnaires revealed some problems with inappropriate

caulking materials, and sticking doors and windows. Some concerns due to reduced natural ventilation were tempered after accommodation to a different mode of house operation. One house ultimately required installation of exhaust fans. Most homeowners reported a significant improvement in comfort level.

Detailed energy monitoring consisted of 15 min digital demand recorder data of the energy consumption of the plenum heaters in each house and timers read biweekly to measure oil furnace operation. Weather data was obtained from the nearest meteorological station. Analysis was performed to remove bad data, to correct consumption data to normal weather (1981/1982 was colder and 1982/1983 warmer than usual) and to develop a heating system load line (heating demand vs outdoor temperature) for each house.

Measured consumption reductions averaged 6% and ranged from -11% to +15%. Five houses showed negative or zero savings; these are ascribed to lifestyle effects, microclimate variations, or the inability of the experimental measurements to discriminate small differences. Average reductions by upgrading category bear the expected relationship to each other. Demand reductions averaged 13% (-6% to +30%). Three houses gave negative or small savings, due to a possible unsealing of one envelope, possibly ineffective basement insulating in another case, or to the confounding effect of manual night-setback in two instances. Again, category reductions follow expectations. The load lines generally exhibit a cross-over at warm temperatures (higher demand after upgrading in the shoulders of the heating season), thought to be due to lifestyle changes caused by the effects of the retrofits.

The NRCC-developed computer program for estimating the space heating requirement of residences, HOTCAN, was used to predict the expected savings. Detailed house data and average estimated natural air change

rates were used as input. This program calculated energy consumptions and demands (both before and after upgrading) that are significantly (80% and 40% respectively) larger than those measured. Predictions of consumption reductions are overstated by a factor of three on average; demand savings are more closely modelled. These results show the difficulty in modelling upgrading effects with a procedure that does not, and cannot easily account for occupant lifestyles and modes of house operation. There are also indications of areas where technical improvements to the program could help, especially in modelling upgrading effects.

To assess the improvements due to airsealing, fan depressurization tests were performed before and after upgrading on all houses. The airtightness results corresponded to the work done and results achieved (eg, decreased drafts) in only half the houses, due partly to repeatability and accuracy difficulties with the fan tests but also to their inability to respond to the effects of the distribution of leaks. A correlation (developed by C.-Y. Shaw, NRCC) to give natural air change rates from fan data gave even less consistent indications of the airsealing work done, again for leak distribution reasons; further development is suggested to cover retrofit situations better. The average of the estimated before and after air change rates was used to give a baseline for the predicted energy and demand reductions.

Assuming upgrade costs annualized over 50 years at a 3% real interest rate, six homeowners see net savings. Adding the savings to the electric utility of the reduced demand after upgrading yields net societal savings for ten houses.

Electric utilities should consider promoting thermal envelope upgrading work if the significant demand consequences found in this experiment are useful to them. Such programs must discount predicted consumption savings, and deal with possible long-term effects of airsealing by promoting mechanical ventilation.

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1 INTRODUCTION

A concerted effort is being made to reduce the space heating requirement of new housing by increasing insulation levels and paying greater attention to the reduction of air infiltration; however, the global savings resulting from this course of action remain limited since the majority of the housing stock that will exist in the foreseeable future has already been built. If a substantial reduction in residential energy use is to be achieved, upgrading of the thermal envelope of existing houses must be undertaken. There is very little information available on the energy savings and especially on the reductions in heating demand (power) based on direct field measurements of various upgrading techniques (1,2).

As well, if demand reductions could be quantified, then economic decisions could be made on the possible trade-off with service entrance costs on conversion to electricity from oil space heating. That is, if one could reliably say that a given upgrading measure would allow a large enough downsizing of the heating equipment on conversion then one would be able to avoid a costly upgrading of the service entrance capacity.

To accurately determine the effect of thermal envelope upgrading, a history of energy use has to be established prior to upgrading, and maintained following upgrading. Since this requires considerable time and effort, energy use comparisons are generally based on calculated values. However, an extensive history of energy use has been established in a group of 49 houses used for a study of dual energy heating systems (3). Energy use and outdoor temperatures were monitored for two heating seasons (1980/1 and 1981/2), with data collected on a 15 min

interval basis. This has allowed determination of design heat losses and energy consumptions.

This project was thus initiated as a continuation of the dual energy field trial in 16 houses, in which various upgrading measures were done. The direct measurement of the effect of such upgradings showed an average reduction of 6% in energy consumption and 13% in heating demand. The work on this field trial also included dealing with the few problems that arose, and noting the costs involved in upgrading existing homes and calculating the offsetting savings. The data were also used to prove the best available predictive model (HOTCAN) with a view to generalizing the conclusions drawn, but the forecast savings were significantly larger than the measured values. This disparity is ascribed to occupant lifestyle effects. The information obtained in this experiment should prove useful in electric utility customer information and demand management programs.

2 FIELD TRIAL DESCRIPTION

2.1 HOUSE CHOICE

The 49 dual energy field trial houses were screened using the following criteria:

a) homeowner willingness to have upgrading work done and monitored, and to pay part of the cost (26 houses).

b) acceptable previous heating demand data.

c) no significant auxiliary heating supply.

d) no significant lifestyle changes contemplated.

e) scope for thermal envelope upgrading.

The resulting houses were visited to ascertain appropriate categories of upgrading and to acquaint the homeowners with the new project. General information on the 16 houses left in the upgrading field trial is included in the Master Data Tables (Appendix A). Detailed descriptions of the "before" condition of the homes can be found in Appendix B. Further details of the heating systems, etc, are contained in reference 3. Note that the 8.3 kW or 4.9 kW plenum heaters used in the dual energy experiment were replaced by 9 kW models during the 1982/3 heating season as a consequence of the legal agreement signed with the homeowners for that experiment. The effect of this change on the results from the thermal upgrading experiment are discussed in Section 4.6.1 1).

2.2 UPGRADING CATEGORIES

The following distribution of categories resulted from the preliminary visits, further analysis and discussions with the technical advisors:

a) Homeowner Airseal: 3 houses (DIY Seal)[1]

The homeowner performed basic airsealing measures such as weatherstripping and caulking on the advice of a qualified energy auditor (Ontario Hydro Residential Energy Advisor). The homeowner was supplied with all necessary materials.

b) Contractor Airseal: 4 houses (Seal)[2]

Local airsealing contractors were employed to reduce the rate of air leakage through the extensive use of caulking and weatherstripping, and the application of insulating foam behind baseboards, along sill plates, around plumbing stacks, etc.

c) Contractor Airseal and Basement Wall Insulation: 4 houses (Seal and Basement)

Local contractors were employed to perform the measures described in category b) and to insulate the basement wall.

d) Contractor Basement Wall Insulation: 4 houses (Basement)

Local contractors were employed to insulate the basement walls (and airseal in the same area, although not throughout the rest of the house). The work in house 71-07 was homeowner performed, although with contractor quality (DIY Basement).

e) Contractor Attic Insulation Increase: 1 house (Attic)

A local contractor was employed to increase the attic insulation to a level presently considered economic (RSI 6.5 (R 37)) (and airseal in the same area).

---

1 Independent of this experiment, the homeowner of house 71-32* had attic insulation added in the summer of 1982.

2 House 71-25 had insulation added to isolate the cold room in the basement.

* Rates Dept. Survey Number 71, house number 32.

It was the judgement of the project team that no category of insulating without airsealing be attempted, because of the potential for causing condensation problems within the wall cavity or attic.

Details of the specific work done in each house were left up to the local contractors employed (subject to scrutiny by the project team to ensure compliance with the requirements of the experiment, and to homeowner approval), and are described in Appendix B.

2.3 UPGRADING COSTS

The sub-contract costs incurred to do the various upgradings are listed in Appendix A, column 14. The total for the 16 houses was $22,180, of which 26% was contributed by the homeowners. The average job cost for each category is presented in Table 1. The costs considered are the sub-contract costs excluding the fan tests (ascribed to the research project) by including the homeowner contributions (their labour was not costed).

Table 1

AVERAGE UPGRADING COSTS

Category	Number of Houses	Average Cost ($)
DIY Seal	3	260
Seal	4	770
Seal & Basement	4	2810
Basement	3	1660
DIY Basement	1	670
Attic	1	1460

To attempt to compensate for the different sizes of jobs, the costs per insulated area (basement or attic) or per living (floor) area (air-sealing) are shown in Appendix A, column 19. Values ranged between:

a) \$0.90 and \$3.00/m^2 for homeowner airsealing, depending on effort expended and on the condition of the house.

b) \$1.80 and \$12.90/m^2 for contractor airsealing. The upper figure may be unrealistically high (separate contractors for airsealing and insulating were utilized), for the next highest value is just \$9.40/m^2. The lower figure is based on an indirect calculation; the lowest directly-calculated value is \$3.60/m^2.

c) \$21.60 and \$31.20/m^2 for contractor basement wall insulation (including drywall and basement airsealing). For those jobs where whole-house airsealing was also done, the costs for basement insulation alone ranged down to \$20.10/m^2.

d) \$7.60/m^2 for the one instance of homeowner-installed basement insulation, without drywall (materials only).

e) \$14.70/m^2 for the one instance of attic insulation increase including attic airsealing (separate contractors were used for airsealing and blowing-in cellulose).

In Section 5.5 are calculated the savings resulting from the consumption and demand reductions occasioned by the spending of these dollars on upgrading. The savings are much more variable than these costs.

2.4 UPGRADING INSPECTIONS

Inspection visits were made during the contractor work to record in words and photographs the methods used and any problems encountered. Observations made in these visits are included in the descriptions found in Appendix B. An album of the photographs taken is available for viewing at Ontario Hydro Research. Some problems encountered with the upgrading techniques used are discussed below.

In houses where airsealing was performed, a variety of materials and techniques were used, some of which are worthy of concern. One franchised airsealing contractor used a caulking that had extremely strong fumes. This was considered unacceptable for interior use and a substitute caulking was found.

Different techniques were used to reduce infiltration in sashless glass slider windows. Application of "V Strip" style weather-stripping proved less intrusive with respect to window operation than weatherstripping that was screwed down against the panes, which made the windows difficult to open and unremovable for cleaning.

Peelable rubber-based caulking was applied to windows in some cases although problems were identified. One particular brand of this type of caulking was easily dissolved when it came in contact with condensation running down the pane, and became brittle, making it difficult to remove. There were also some general concerns expressed regarding the possible difficulties in emergency egress should the windows be sealed shut.

It was noted that weatherstripping applied to doors prevented proper closure in some instances.

Basement insulation consisted of either wood framing with glass fibre batts, wood framing and rigid expanded polystyrene board, or extruded polystyrene board with custom fasteners. When discussing different basement insulation techniques with contractors prior to upgrading, an unfortunate situation arose. Some contractors advocated the use of two-component urethane spray foam for basement insulation. This could be built up to a reasonable thickness for wall insulation and could provide extremely quick and effective sealing of the sill plate area. However, upon investigation (4), it was discovered that the use of this material

is not officially sanctioned for use as an insulating material, but is approved for use as an airsealing material. This constraint prevented us from using urethane spray foam as wall insulation, although two contractors used it for sealing the sill plate area.

3 ENERGY AND DEMAND PREDICTIONS

3.1 METHOD

As a way of generalizing the results of this field trial, predictions of energy consumption and space heating demand reductions due to the thermal envelope upgradings actually performed in the 16 houses were made. HOTCAN, a microcomputer program originally developed by the Division of Building Research in Saskatoon for estimating the space heating requirement of residences (5,6), was chosen as the most appropriate predictive model. Further development of this or similar programs is occurring in a number of agencies, but this work was not well advanced when the model was first needed in this project. Thus the early version, HOTCAN 2.0, was used. This choice should not significantly affect the predictions of space heating demand. Later versions of the program have more sophisticated evaluations of energy consumption, but these improvements would not significantly affect the calculations for these ordinary (ie, not passive-solar) houses, and could well be masked by individual lifestyle effects. One of the fundamental assumptions of this analysis is that no significant changes in lifestyle occurred between the "before" and "after" heating seasons. This implies that predictions of the reduction in energy used after upgrading should be better modeled than is absolute consumption. However, lifestyle modifications "caused" by the retrofits cannot be modeled by this or any other simple calculation procedure without invoking a priori assumptions about such human behaviour.

Because the natural air change rate is an input to HOTCAN, only the transmission heat loss factor is a prediction of the program. Comparison of the HOTCAN outputs and measured data then gives an indication of

the appropriateness of the choice of air change rate (based on the airtightness test results, see section 4.1).

3.2 INPUT DATA

The data input to HOTCAN are detailed in Appendix C. The component areas (inside dimensions) were taken from site measurements or house plans (original or redone); they are given to 0.1 m^2. The insulation levels (given to RSI 0.01) were derived from site inspection, knowledge of building construction eras, and engineering judgement; and modified for composite wall and framing effects according to U-value tables derived for an improved heat loss calculation work sheet (7) (except for below grade components, for which nominal insulation levels are needed).

To give the transmission-only heating load, the natural air change rate was set to zero. A 0.5 ac/h rate was also used to show the sensitivity of the heating load to air leakage. The same values were assumed in the calculation of monthly heating consumptions.

Weather data were available for Toronto and Ottawa in HOTCAN 2.0. Data for Kingston and North Bay were obtained from the revised version (8). The nearest data location was used for each house as noted in Appendix C. The other detailed assumptions used are also outlined in that appendix.

3.3 RESULTS

The full printed HOTCAN outputs for each house (four cases: before and after, 0.0 and 0.5 ac/h) are gathered in Appendix C. The annual heating consumptions (ratioed to the actual normal degree-days) and predicted

design heat losses (ratioed to the actual design temperature differences) are presented in Appendix A, columns 21 to 24.

From the historic oil consumption (column 9) can be calculated normal annual consumption using seasonal efficiency, oil heating value (section 4.4.1 b)) and normal vs actual degree-days; see column 10. Comparison with the predicted consumption (with average ac/h) (column 21) shows an average overprediction of 100% (ranging from 30% to 250%). The particular assumptions of basement temperature, heat gains, natural infiltration rate, etc may contribute to this error, but are not expected to account for anywhere near all the inaccuracy. (For instance even assuming 0 ac/h brings the prediction below the historic value for only one house (71-32).) Any retrofits or other conservation efforts since 1977/1980 would only increase the problem. Without a detailed investigation of HOTCAN (beyond the scope of this study) no full explanation of this state of affairs is possible. If HOTCAN's modeling were wrong by the same factor both before and after upgrading, then the percentage reductions would be more closely predicted than the absolute values are; this does not turn out to be the case, again for lifestyle-related reasons (see Sections 4.5.4, 4.6.2, 5.1.1 and 5.4).

Comparison of the before design heat losses (using the average of the before and after air change rates from Section 4.1.2, see column 29) with the oil furnace operating output capacity (calculated from the data in Section 4.4.1 b), except using steady state efficiency, and shown in column 11) indicates the usual large oversizing and large range of oversizing (3, Section 11): 20% to 160%. This suggests no large overprediction of the heat losses, and Section 4.6.2 shows just a 40% average overprediction.

The percentage reductions in energy and demand (ie, design heat loss) (using the average of the before and after air change rates from

Section 4.1.2) are listed in Table 2. There are no predictions for the airsealing-only cases, nor for the airsealing component of the other categories.

Table 2

HOTCAN PREDICTIONS
(average ac/h)

Category	House Number	Percentage Reductions Energy	Demand
DIY Seal	14	-	-
	26	-	-
Seal (Basement)	22	-	-
	25	1	1
	27	-	-
	33	-	-
Seal & Basement	04	44	33
	09	29	21
	12	39	27
	34	28	20
Basement	06	25	14
	10	23	12
	15	21	15
DIY Basement	07	41	31
Attic	28	14	11
Attic & DIY Seal	32	11	8
Average (excluding airsealing, ie, assuming - is 0)		17	12

The two main characteristics of these predictions are:

a) their relatively large magnitudes in most cases, and

b) the fact that the energy reductions are always larger than those for demand.

4 MEASUREMENT TECHNIQUES, RESULTS AND ANALYSES

4.1 AIRTIGHTNESS TESTS

To give an indication of the airsealing improvements achieved, airtightness tests were commissioned both before and after the thermal upgradings.[3] These tests were done by the airsealing contractors except for the houses in Barrie, for which an independent tester was hired (the local contractor did not have a testing capability). Considerable effort was expended to have all the tests done in accordance with the then latest draft of CGSB Standard 149-GP-10M (9), but equipment limitations and operator experience at variance with the standard test procedure made perfect standardization unattainable.

4.1.1 Results

Details of the test results and analyses are presented in the data sheets in Appendix D. Most of the tests meet all the data verification requirements of the latest draft of the CGSB standard (9a). (All but two meet the fourth draft's requirements.) The final test outputs (relative equivalent leakage areas) are also shown in column 25 of Appendix A together with the resulting airtightness reductions (column 26). The comparison of the 'before' and 'after' airtightness results shows possible difficulties in up to half the houses tested (and thus brings all the tests into disrepute). In houses 71-04, 71-09 and 71-25, the near-zero reduction in airtightness does not correspond to the amount of sealing work done (although the contractor for home 71-09

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[3] Work had already begun on house 71-07 before this experiment was initiated, so no "before" test is available for this house.

was not an experienced airsealer) nor to the evident reduction in natural infiltration actually observed by the homeowners. The test equipment used in house 71-04 seemed to have calibration difficulties which could have contributed to the problem. The increase observed in house 71-10 (where a small reduction would be expected) was partly due to difficult-to-close slider windows and a particularly ill-fitting attic hatch, which was disturbed just before the second test. However, the increase is so large that we must entertain the possibility that a real "opening" of leakage sites occurred, either as a result of the upgrading work (seemingly unlikely) or independently. Because sealing as performed in this project normally results in reductions averaging 40% (and often more in older houses), the relatively low reductions for houses 71-27 and 71-33 are also under suspicion. In contrast, the large reduction for the attic airseal and reinsulation (house 71-28) also is questionable. The large reduction in house 71-32 is probably more due to the attic work done than the homeowner airseal (although a fair amount of material was expended there). For most of these troublesome results, no specific cause is obvious, although the general accuracy of individual tests (often taken as $\pm$10%) plus the repeatability problems due to retest, especially in different weather conditions, may explain some of the difficulties encountered. The other main impediment to the usefulness of fan tests is their lack of discrimination between leaks which are located where natural pressure differences will cause significant air flow and those that are not (see Section 5.2).

Within the constraints discussed above, the test results give a rough indication of the airtightness level of these test homes. The results are expressed in Column 25 as relative equivalent leakage area (ELA), which is the ELA in cm^2 divided by the exposed[4] surface area of the

[4] The latest draft of the CGSB standard uses a building envelope area which includes the below-grade portions to give a normalized leakage area.

envelope under test, in m^2. The relative ELAs for the houses before upgrading averaged 3.9 cm^2/m^2 and are distributed from 2.7 cm^2/m^2 to 5.6 cm^2/m^2. As a point of comparison, results from a Canada-wide airtightness survey (11), done on houses recently constructed to current practice, showed relative ELAs in Ontario ranging from 1.7 cm^2/m^2 to 7.0 cm^2/m^2 with an average of 3.7 cm^2/m^2. Elsewhere in the country, relative ELAs were measured as low as 0.7 cm^2/m^2. The present houses are thus typical of normal construction in Ontario, which is leaky compared to the best construction practice now being used in Canada.

4.1.2 Correlation

Natural air change rates were derived from the measured fan depressurization test results using C.-Y. Shaw's correlation (10). This correlation was developed from fan tests in which intentional openings were not sealed, whereas the CGSB standard specifies sealing them. However, results from the Canada-wide airtightness survey (11) showed little significant difference between the sealed and unsealed results (approximately 10%). Using the sealed data obtained in this experiment will add some extra error to the use of the correlation.

In order to use the correlation, one must specify the weather conditions for which the natural air change rates are needed. (Note that the weather conditions during the fan depressurization test do not define the correlation because the fan results are, to first order, independent of the weather.) For design heating loads, the inside-outside temperature differences range from 39°C to 50°C (Dundas to North Bay). From analysis of Toronto International Airport detailed weather data (12), the mean wind speed during design conditions (outside temperature = -18°C) is 15.9 km/h (4.4 m/s). Winds elsewhere in Ontario are not significantly different from this (13). These conditions fall

into C.-Y. Shaw's Type III ($20°C < \Delta T < 40°C$, $3.5 \text{ m/s} < V < 7 \text{ m/s}$), for which

$$I = 4.53 \frac{C}{v} \qquad [4\text{-}1]$$

where I is the natural air change rate (ac/h)

v is the house volume (m^3)

C is the fan test flow coefficient ($L/s.Pa^n$)

This calculation is shown in Appendix A, column 27, with the ratio of after to before predictions in column 28.

For monthly heating consumption, the relevant wind speeds are not much different than those discussed above. The inside-outside temperature differences vary significantly depending on the month and the location. However

a) HOTCAN has no provision for varying the air change rate;

b) The months with significant heating consumptions are all Type III;

c) The other months are Type II ($\Delta T<20°C$; $V>3.5$ m/s) for which detailed wind information (speed and direction) is needed to calculate the correlation;

d) The average heating season ΔT is close to 20°C, the dividing line between Types II and III;

e) The two Types give similar results if the house is exposed to the prevailing wind (10, Figure 6).

It was thus decided to use the Type III correlation for all the heating consumption calculations.

The natural air change rate predictions give increases after upgrading in 5 cases. For houses 71-14, 71-25, 71-04 and 71-15, there is a corre-

sponding significant decrease in the fan test flow exponent (n) because of the upgrade (see Appendix D). When temperature or wind effects are individually dominant (C.-Y. Shaw's Types I or II, respectively) such changes in n strongly affect the correlation results. Specifically, a decrease in n would decrease the after/before air change rate ratio (as required). A few other houses with increases in n (71-22, 71-06, 71-28, 71-32) would show an increase in the ratio, but they tend to have low ratios already. House 71-10, the other house with a ratio greater than one, would not be particularly affected by an n-based correlation, but there are already difficulties with its fan tests as discussed in Section 4.1.1. Although these results in no way indicate what an altered correlation should be, they do suggest that some dependence on n may be necessary to properly correlate air change rate and airtightness in the case of retrofit changes to the same residence. This dependence on n may be a surrogate for the dependence on the type and distribution of leaks. Appendix D and Section 5.2 discuss this point further. As well, testing of the correlation (10, Figures 8 and 9) suggests a prediction accuracy of just $\pm$25%. This makes distinguishing small changes due to upgradings somewhat problematic.

These predictions are compared in Section 5.1.2 to the differences between actual measurements and the HOTCAN transmission loss predictions. This comparison indicates that the correlation is none too appropriate for predicting air change rate reductions after airsealing from fan test results. Note that these predictions take no account of differences in infiltration-inducing weather between the 'before' and 'after' years. It was thought sufficient to normalize weather based on heating degree-days. A new concept, infiltration degree-days (24), would tell the tale, but requires hourly coincident temperature and wind and much calculation for its determination. This significant extra effort was deemed not justified by the expected modest increase in the accuracy of the weather normalization.

The absolute values of the air change rate predictions (ranging from 0.14 ac/h to 0.77 ac/h) are as expected for typical construction. For the purposes of calculating energy and demand reductions, the average of the before and after air change rates was assumed (see Section 3.3).

4.2 HOMEOWNER QUESTIONNAIRES

In order to monitor the homeowner's reactions to the upgradings and any changes in house operation (eg, increases in condensation due to the airsealing), informal and formal surveys were conducted throughout the experiment as follows:

a) informally, during the upgrading inspection,

b) informally, through the regional staff whenever questions or problems arose,

c) as a small part of the questionnaire to gather detailed data concerning the house construction, in January 1983,

d) follow-up survey, in June 1983,

e) another confirmatory survey, in the fall of 1983.

The formal questionnaires, together with a compilation of the answers and informal comments are included in Appendix E.

A number of homeowner complaints were received soon after upgrading. Most were related to a decrease in natural ventilation after airsealing, coupled with the normal increase in indoor relative humidity in the autumn. In part, the initial comments reflect the need to get used to a new regime of house operation. More importantly, the lack of mechanical ventilation devices to deal with a lowered natural ventilation rate is evident in those cases where significant problems are described. Still,

the availability of openable windows means that such problems need not get out of hand. Ontario Hydro regional personnel kept an eye on such problems, and offered advice concerning moisture control, etc to the homeowners.

Generally, the responses to the June 1983 survey were much more temperate than those received immediately following the upgrading (fall 1982). Some criticisms of the upgrading workmanship were noted, although most homeowners expressed satisfaction. The majority of homeowners indicated a significant improvement in comfort level. Three respondents felt that the thermal upgrading had caused problems of increased humidity or poor air quality. Other respondents did not report any change in this regard. (One reported an improvement in air quality.)

The fall 1983 responses tended to confirm the June results.

4.3 HOURLY MONITORED DATA

The primary monitoring instrumentation was a digital demand recorder (DDR) connected to the plenum heater in each house. This recorded the electrical energy consumption in each 15 min interval throughout the heating season. This report deals with the data from the 1981/1982 (3) and 1982/1983 heating seasons, the latter beginning after the completion of the upgradings in October/November 1982 (Appendix A, column 12; see column 13 for the specific data collection starting dates; collection of data just prior to upgrade completion is considered to have a negligible effect on the analysis), and continuing until mid-May. Monitoring was resumed for the 1983/84 heating season in 13 of the houses (3 houses were sold in June 1983 due to the relocation of the owners); this data will be presented and analyzed in a separate report.

The DDR data was recorded on magnetic tapes which were changed monthly. These tapes were computer-translated to give engineering-units output. From a detailed manual review of these data and the results of preliminary data analysis, a number of meter multiplier and manual reading (used as checks) errors were identified and corrected. Also, metering and equipment outages that caused meaningless zeros were found and verified by showing

a) that heating was required, based on the concurrent outdoor temperature, and

b) that malfunctions (eg, plenum heater breakdown) had occurred.

These meaningless zeros were deleted before further analysis was carried out. Loss of data occurred (from February 10, 1983 to the end of that season) in house 71-15 as a result of a failure in the metering equipment. Another anomaly discovered was the use of manual night-setback of the thermostats in houses 77-12 and 71-22, indicated by abnormally low consumptions at night (again, in comparison with the outdoor temperatures). (This state of affairs was confirmed with the homeowners.) Data for the appropriate night hours were deleted for these two houses to attempt to remove the effects of setback. However, the remaining data has lower quality than for the other houses because

a) roughly one-third less data is utilized, and

b) thermal mass/time constant effects mean that the indoor temperature variations affect the daytime data to some extent.

The Fall 1983 survey revealed manual night-setback in houses 71-06 and 71-07 (also daytime setback) as well, although the DDR data gave no clear signal. The nighttime data was thus <u>not</u> deleted before analysis; the results may show some extra effect because of this.

Hourly outdoor temperatures were obtained from the nearest weather station, as indicated in column 8 of Appendix A. The DDR data were accumulated over hourly intervals to correspond to the available temperature data. These data were analyzed together to give a heating demand profile as described in section 4.6. The DDR data were summed to give monthly consumptions for comparison with the HOTCAN predictions (see section 4.4).

4.4 MONTHLY SPACE HEATING ENERGY CONSUMPTION

As an indication of the energy saving created by a given upgrading, and to compare to the HOTCAN predictions, monthly space heating energy consumptions were abstracted from the monitored data. The plenum heater consumptions were obtained by summing the DDR outputs over calendar months. To this must be added the relatively small amount of back-up oil consumed, as described below.

4.4.1 Oil Usage

Oil usage was monitored by timing oil furnace operation. Arrangements were made for the homeowners to note the timer reading twice a week; back-up readings were taken in some instances by the DDR tape changers. However, some data gaps exist as indicated in the results presented in Appendix F. In most instances, usage is relatively low, so that lack of information on the oil contribution does not cause a significant error (see Appendix A, column 32).

A number of corrections and factors need to be applied to these data to obtain useful monthly heating energy consumptions:

a) linear corrections to change data reading dates to month-end, and

b) three multiplying factors to convert operating time to energy content:

- oil furnace seasonal efficiency, assumed to be 13% less (14) than the measured steady-state efficiency (3, Appendix A, column 11)

- measured oil flow rate through the nozzle (3, Appendix A, column 13)

- measured oil heating value (3, Appendix A, column 15).

The data and these calculations are shown for each house in separate tables in Appendix F.

4.4.2 Total Consumption

Because the data do not always correspond to complete months, average daily consumptions are used to obtain monthly total (electrical + oil) consumptions. To account for weather variations (1981/1982 was cooler than normal and 1982/1983 warmer), base 18°C degree-days for Toronto International Airport (now Pearson International Airport) were used to give normal daily consumptions. (The gross weather fluctuations are assumed similar throughout the province.) These daily data for before and after upgrading were compared month-by-month from November to April (the significant part of the heating season for which data is available) to give the consumption *reductions* shown, together with the supporting calculations, in Appendix F, Tables F1. The degree-day ratioing was checked by calculating total monthly consumption divided by monthly

degree-days: the relative consistency of this "slope"[5] in the heating seasons for all houses confirms the appropriateness of using these degree-days to obtain normal consumptions. These results neglect oil usage where detailed data is not available.

The monthly after/before consumption ratios presented in the second last columns of Tables F1 in Appendix F show a consistent pattern: although roughly constant in the coldest part of the winter, the ratios increase significantly at both ends of the heating season. Most houses exhibit this effect, which suggests that consumption increases after upgrading in the shoulder seasons. This phenomenon is discussed further in Section 5.4.

4.4.3 Comparison with Predictions

Without going into a detailed analysis, comparison of the monthly normal consumptions (Tables F1) and the HOTCAN "auxiliary heat required" (Appendix C), yield the following observations:

a) the HOTCAN predictions are roughly a factor of 2 too high, similar to the situation with the historic oil consumption (Section 3.3),

b) the monthly profiles are quite similar, except

c) in the shoulder seasons, the actual consumptions fall off much faster than do the predictions. This suggests homeowners turn off their heating systems early in the spring and turn them on again late in the fall, depending on internal gains and their houses' thermal inertias to maintain comfort conditions (possibly with wider temperature excursions than their thermostats would allow). HOTCAN predicts to a strict thermostat setting,

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[5] By analogy with the demand vs temperature slope discussed in Section 4.6.1.

based on mean monthly temperatures (another source of error, particularly in the shoulder seasons).

4.5 YEARLY ENERGY CONSUMPTION

The yearly total (oil + electricity) energy consumptions (with various beginning and ending times) are displayed in Appendix F, Tables F1. These data are altered using degree-days as in Section 4.4.2 to give normal consumptions for the year, as shown in Table F2 and Appendix A, column 30. As a point of comparison, the standard annual space heating energy consumption of Ontario Hydro customers is generally taken to be about 15 000 kW•h (15).

4.5.1 Oil Usage

The proportion of the total consumption provided by oil is listed in Appendix A, column 32. For 1981/1982 it ranges from 0% to 36% (average: 8.2%) while for 1982/1983 the range is 0% to 21% (average: 4.6%). In most cases this proportion is small enough that missing, extrapolated etc data do not affect the overall results significantly. The smaller average usage after upgrading reflects the milder 1982/1983 winter (12.4% milder based on degree-days in Toronto) coupled with the control of the oil furnace on the second stage of a two-stage thermostat.

4.5.2 Historic Comparison

The before totals (Appendix A, column 30 Before) can be compared to the 1977/1980 averages based on oil usage (column 10) to indicate the consistency of space heating energy consumption. On average, usage shifted just 300 kW•h/year, a negligible amount; individual differences

ranged from 200 kW·h/year to 5 700 kW·h/year, and never more than 35% of the historic consumption. Six houses show reductions from the historic usage, probably due to retrofitting activities. The majority have increases, suggesting lifestyle changes. Some of the variations may be due to the need to make crude weather corrections.

4.5.3 Consumption Reductions

The percentage reductions in space heating consumption based on the results in Table F2 (Table 3 and Appendix A, column 31) are somewhat different than those shown in Tables F1; the former are deemed more appropriate because they include (conservative) provision for missing oil data. The actual degree-days corresponding to the measured data shown in Table F2 indicate the proportion of the heating season covered by the measurements.

The category average reductions bear the expected relationship to each other, although the absolute reductions are relatively modest. The uniqueness of each house and its occupants and of the specific upgradings performed allows for the individual variations seen. Houses 71-26 and 71-32 show consumption increases; both have absolute reductions which disappear when the weather variations are discounted. The reduction expected for house 71-26 (DIY seal) is small, and lifestyle changes may have masked the pure result. Of course, lifestyle changes caused by the upgradings (eg, more window openings due to higher moisture levels) are a legitimate part of this experiment (but are not predictable from building envelope properties alone, see the next section). Two of the four night-setback houses (71-06 and 71-22) show zero consumption reductions. The zero reduction for house 71-25 is not readily explained, although a significant by-pass leak from the basement to the

Table 3

CONSUMPTION REDUCTIONS

Category	House Number	Consumption Reductions (%) Individual	Category Average
DIY Seal	14	5	-3
	26	-11	
Seal	22	0	
	25	0	3
	27	9	
	33	2	
Seal & Basement	04	9	
	09	7	11
	12	15	
	34	14	
Basement	06	0	
	10	5	8
	15	14	
DIY Basement	07	11	
Attic	28	13	6
Attic & DIY Seal	32	-2	
Average		6	

attic through the second storey heating duct passageway was observed during the "after" fan test.

4.5.4 Comparison with Predictions

Because the predictions in column 21 of Appendix A use before/after averaged air change rates, the absolute comparison is made with the average of the before and after normal yearly consumptions (column 30). Consumption is overpredicted from 20% to 170%, and 80% on average. This error is comparable to that seen with respect to historic oil consump-

tion in Section 3.3, and cannot be fully accounted for by the assumptions used in the predictions except to the extent that lifestyle intrudes.

Predictions of percentage consumption reductions (Table 2 vs Table 3) are grossly overstated in most cases: a factor of 3 on average. And the predictions do not include airsealing effects. The fact that these results are much worse than the absolute comparisons points out the difficulty in dealing with differences of like-sized quantities. Part of the problem in predicting reductions is due to the trouble already seen in predicting absolute values. The other possible source of error could be a real upgrade-caused lifestyle effect which mere physical modeling of the building envelope can never uncover. This is discussed further in Section 5.4.

4.5.5 Electric Billing Data

As a check on the DDR data collected, billing records were obtained for most houses (Table F3). With some assumptions as detailed in Table F3, the difference between the billed consumption and the plenum heater energy gives an indication of average domestic usage (Appendix A, column 33). This value varies by a factor of four between houses, a not-unexpected result. The average of the individual usages is only somewhat higher than the value assumed in the HOTCAN predictions (38 vs 32.3 kW·h/day). Although specific houses' predictions would change if actual usage were input, the overall overprediction would not be significantly affected (see Appendix C.2).

Where detailed billing information is available, the domestic usage is relatively constant in most cases. Some houses show changes between the two monitored years although this result may be an artifice of the

assumptions made, in some cases. Five houses show increased domestic usage after upgrading and six show a decrease. On average there is a 3 kW·h/da reduction (about 1000 kW·h over the year); this could result in an increase in space heating, thus, contributing to a lower-than-expected upgrading saving. The worst case (house 71-07) shows a 36% (13 kW·h/da) decrease, but this may be a case of insufficient information. There are some indications of intensified usage in the winter, suggesting supplementary electric space heating.

4.6 SPACE HEATING DEMAND

4.6.1 Analysis Technique

The DDR/temperature data embodies the overall space heating characteristic of each house ie, how heating consumption varies with the weather. The usual expression of this characteristic is the heating demand at design weather conditions (as defined in building codes), ie, the required heating equipment capacity. The more general expression is the rate of change of demand with temperature. This is the overall transmission coefficient of the house (kW/°C), under the assumption that the total house heat loss curve is a straight line parallel to the heating system load line actually determined (as described in item 3, p 31). We are principally concerned with the reduction of this characteristic after the thermal envelope upgradings. The determination of this reduction is complicated by the following conditions, some of which are peculiar to this experiment:

a) The plenum heaters generally do not supply all the space heating energy for the houses, so that the hourly consumptions at design conditions are likely to include an undetermined amount of backup oil energy. The oil furnace is run on the second stage of a two-stage thermostat. The demand/temperature slope must thus be determined from a limited range of outdoor temperatures.

b) A number of weather effects other than temperature are not accounted for, including wind, precipitation and solar radiation. This introduces scatter about the demand/temperature line.

c) Household operation and lifestyle effects also contribute scatter. Besides changes that normally happen year-over-year, there is the possibility that the upgradings themselves might "cause" alterations, such as extra ventilating in tightened houses; these might result in systematic shifts between the "before" and "after" data.

d) The situations described in b) and c) seem to intensify close to the house balance temperature, that temperature below which heating equipment operation begins to be required. This may be due to a somewhat unstable mix of overheating due to solar and other gains, increased ventilation (eg, opening windows to compensate), thermostat overshoot, etc.

e) Close to the balance temperature, the cycling of outdoor temperature theoretically requires cycling of the house's space conditioning equipment between heating and cooling. None of the houses has an air-conditioner, nor is cooling normally utilized until much warmer conditions (rather, natural ventilative cooling and occupant adaptation are substituted). Thus measured heating consumptions in this temperature range are not balanced by cooling effects so that the graph of heating demand vs temperature levels out with increasing temperature around the balance temperature. This phenomenon imposes an upper limit to the temperature range from which the house characteristic can be determined.

f) Digitizing errors (due to the accumulation, on the DDR tapes over the fixed 15 min time intervals, of magnetic pulses corresponding to fixed amounts of energy) and the interaction with the cycling of the thermostat also introduce scatter. (The accumulation of the consumption data on an hourly basis reduces these sources of scatter.)

g) The temperature data used does not correspond exactly to the local conditions at each house; for some houses the nearest weather station is quite far away. Temperature offsets thus exist between actual conditions and the data utilized. This has no effect on the determination of the demand/temperature slope if the offsets remain constant ie, the airport data closely tracks the house environ-

ment. Short-term variations in these temperature offsets again add scatter.

h) The heating system reacts to changes in outdoor conditions only after a delay defined by the thermal mass and conductivity of the house envelope. This introduces a temporal offset when the DDR and temperature data files are merged using the same absolute time. Effects as in g) are then produced. An additional and systematic effect in this situation is the possible difference in the delay (ie, house time constant) before and after upgrading due to the changes made to the envelope.

i) To complete the commitment to the homeowners under the previous dual energy field trial, the experimental plenum heaters were replaced with slightly larger, commercially-available models in the spring of 1983 (see Section 2.1). This decreases the temperature at which the oil furnace begins to operate on the thermostat's second stage, but the useful temperature range discussed in a) is still defined by the previous plenum heater size.

j) The assumption that demand varies linearly with temperature is largely, but not completely, true. For instance, the energy loss due to air leakage increases linearly with decreasing temperature; however, the rate of air leakage depends in part on the inside-outside temperature difference non-linearly (24) (the stack effect). Thus the overall variation of demand due to air leakage is non-linear. Similarly, the increase in the resistance of insulation as its average temperature is lowered (roughly 10% from room temperature to design conditions) makes the demand vs temperature curve non-linear. Floating basement (or other room) temperatures also introduce non-linearities, as do occupant lifestyle effects which vary with outdoor temperature. All these effects tend to become stronger at lower temperatures, which are excluded because of a).

The above considerations, and the typical plot of heating demand vs outdoor temperature shown in Appendix G, Figure G-1, indicate the significant scatter inherent in the data. This necessitates a statistical, best-fit analysis to determine the houses' characteristic slopes. A number of analysis techniques (including that used previously for the 1981/1982 data (3)) were tried before deciding on the one, outlined step-by-step below, as the most correct method.

1. The hourly plenum heater energy consumptions (ie, hour average electric heating demands) were combined with the corresponding outdoor temperatures (with deletions as discussed in section 4.3).

2. From plots of demand vs temperature, engineering judgement was used to determine the appropriate upper and lower temperature limits to exclude the phenomena discussed in a), d) and e) above. After these limits were chosen separately for the before and after data for each house, a common set of limits was adopted (the greater of the lower limits and the lesser of the upper) to avoid any possible temperature anomalies in the before/after comparison; these limits are shown in Appendix A, columns 40 and 41. The extent of the deletions occasioned by imposing these limits (plus those due to bad data) is indicated by the number of observations used compared to the total number available, shown in columns 38 and 39.

3. The remaining data for each house was sorted into around 137 temperature bins equally spaced within the temperature range defined in step 2. The average demand in each bin was determined. The best-fit straight line (termed the heating system load (HSL) line) through these data was calculated, weighing the data by the number of points making up the average demands. The slope of this line and its standard error (in all but 2 cases less than 1% of the slope) are presented in columns 42 and 43. The goodness of fit is indicated by an R^2 close to 1 (see column 44); the values are above 0.9 in 23 of the 32 cases. This confirms the appropriateness of modeling the HSL lines as straight lines. The cases with data problems discussed in Section 4.3 (houses 71-12, 71-15 and 71-22) do show somewhat higher slope standard errors and lower R^2 than for the bulk of the data, but not enough so to indicate significant difficulties.

4. Using the normal outside design temperature for each house location (not for the weather station used for the temperature data) and assuming 22°C inside, the design heat loss (column 45) (an indication of the required furnace size) was calculated from the HSL line slope.

Further details, and example plots to illustrate the analysis technique can be found in Appendix G.

A second analysis technique using daily averages was tried to see if such data are adequate. Also, daily averaging allowed retention of nighttime data in the night-setback houses (this assumes a consistent setback amount and duration). Days were included which had data (after step 2 above) for at least 20 h; this is a compromise between getting a good daily average and having very few data points. The number of days used is shown in Appendix A, column 34. The best fit HSL lines have R^2 (column 37) much lower than for the hourly analysis and standard errors (column 36) often greater than 10% of the HSL slopes (column 35). The slopes are generally within 10% of the hourly results, but are sometimes significantly different. It is concluded that daily data gives a much less accurate indication of the heating demand characteristic of a house. These results are thus not considered further.

4.6.2 Results

Eleven of the houses have measured design heat losses (Appendix A, column 45) less than 10 kW (the minimum available central electric furnace size). Comparison of the design heat loss with the historic furnace capacity (column 11) again shows the expected oversizing (an average of 140%, and up to 300%, although house 71-04 has just 6% excess capacity).

There are significant demand reductions (Table 4 and column 46) in all but 3 cases. House 71-22 may show the complication introduced by manual night-setback (another setback house, 71-12, also shows a reduction much less than for the other houses in its upgrade category). The airtightness test results on house 71-10 suggest a possible unsealing of the

structure, consistent with the demand increase seen here, which swamped the effect of basement airsealing and insulation. The small decrease measured for house 71-06 may be the result of manual night-setback, as well as the difficulties in adding insulation to a partly-finished basement (both inside and outside insulation were applied; the transition, and the stairwell work, may not be too effective). The category average reductions bear roughly the expected relationship to each other, although the homeowner airsealing gave larger reductions than anticipated.

Table 4

DEMAND REDUCTIONS

Category	House Number	Demand Reductions (%) Individual	Category Average
DIY Seal	14	19	13
	26	7	
Seal	22	-4	
	25	18	10
	27	18	
	33	8	
Seal & Basement	04	30	
	09	21	20
	12	10	
	34	21	
Basement	06	1	
	10	-6	9
	15	23	
DIY Basement	07	17	
Attic	28	20	15
Attic & DIY Seal	32	10	
Average		13	

Comparison of the percentage energy and demand reductions house-by-house shows no obvious relationship; neither does the category comparison presented in Table 5. On average though, the demand reductions are

twice the energy decreases. This has clear implications for utility support of upgrading, as discussed further in Section 5.5.

Table 5

CATEGORY REDUCTIONS

Category	Number of Houses	Percentage Reduction	
		Energy	Demand
DIY Seal	2	-3	13
Seal	4	3	10
Seal & Basement	4	11	20
Basement	4	8	9
Attic	2	6	15
Average		6	13

Absolute comparisons with the HOTCAN results are again made using the averages of the before and after values because of the averaged air change rates employed in the predictions. HOTCAN gives values 40% larger than the measurements on average (ranging from -10% to +110%). This is better than the consumption comparison, as it should be (there are many fewer complications and assumptions involved), but is still rather too large for confidence in predictions using HOTCAN.

Prediction of the percentage demand reductions is quite close, on average and in most individual cases, to the actual percentage decreases, although the effect of airsealing is not included in the HOTCAN results. This close correspondence may thus be somewhat fortuitous.

Because peak heating loads for these dual fuel houses perforce include an oil contribution, for which 15 min demand data was not collected, no attempt has been made to calculate load factors or develop load profiles. It is assumed that the measured reductions in design heat loss give a fairly accurate indication of the effect of upgradings on the demands imposed on the electrical distribution system (see Section 5.5 and Appendix H).

5 DISCUSSION

5.1 PREDICTIONS

5.1.1 HOTCAN

As detailed in Sections 3.3, 4.5.4 and 4.6.2, HOTCAN does not predict either energy or demand absolute values or reductions very well. HOTCAN was initially developed for and proved on low energy Prairie housing, which may render it less appropriate for the ordinary Ontario houses in this study.

The two main areas of possible technical uncertainty in the calculations are basement heat loss and air change rate. The former is in general the largest component of the total heat loss. A number of effects could account for the over-generous predictions for basements:

- incorrect above-grade wall resistances (especially for uninsulated walls due to the inappropriateness of high wind air film coefficients close to the ground or extra insulation from piled snow),
- two-dimensional heat flow in the header area,
- different-than-assumed soil thermal conductivity conditions, and
- floating rather than thermostat-fixed basement temperatures.

The other major area of difficulty is using this model for airsealing retrofits when the critical parameter (the natural air change rate) is a user-specified input. This is compounded by the trouble in determining this quantity independently, from fan tests. (As described in Section 4.1.2, this necessitated the use of average air change rates to

obtain baseline consumptions and heat losses for percentage reduction determinations.) Incorporation of an infiltration model (23, 24) into HOTCAN would increase its usefulness in upgrading situations.

Other possible technical reasons for HOTCAN's poor performance includes:

- the temperature dependence of insulation resistance (see Section 4.6.1 j),
- incorrect accounting for such specific house details as enclosed or attached garages, crawl spaces (connected to or sealed from the house), overhangs, partly insulated basements, etc,
- no provision for thermostat set-back schedules,
- temperature fluctuations (whole house or individual rooms) due to thermostat droop, ill-balanced ductwork or low cycle rates from significantly oversized furnaces,
- dynamic effects not captured in the monthly average weather data used nor in the monthly energy calculations.

Lifestyle effects are also probably responsible for a significant part of the discrepancy between measurement and model. The calculations in Appendix C.2 suggest that it is important to more closely define such house operation and occupancy details as:

- thermostat setting (including setback schedule),
- when the central furnace is turned on in the fall and off in the spring,
- basement temperature (level and variability),
- domestic electricity usage (from previous summertime bills),

- number of occupants and their times in the house,

- window opening behaviour, etc.

Not all of these items can be closely defined without making a detailed survey of or measurements on the specific house and homeowners. And some of these parameters can change because of the upgrading; such changes can probably never be determined a priori by, for instance, defining the energy philosophy of the occupants with a questionnaire.

With the refinements discussed in Appendix C.2, the absolute consumptions and demands are more closely predicted, but still not enough so for HOTCAN to be a useful tool for planning upgrading projects. Improvements in the technical areas discussed above may help this situation. Such improvements would need new research in some cases, or expanded application details. The house data and energy and demand measurements from this experiment could be useful in proving any such refinements. There is still the possibility that:

a) such developments of HOTCAN would not fully correct the situation, and /or

b) the upgrade-caused lifestyle changes are large enough that reduction predictions cannot successfully be made.

In either of those cases, no definitive forecast of upgrading effects would be available; this would have the effect of increasing the uncertainties involved in promoting thermal envelope retrofits.

5.1.2 Air Change Rates

With the assumption that HOTCAN accurately calculates the transmission components of heat loss, a measure of the heat loss due to air change can be had by subtracting the 0 ac/h HOTCAN calculation of heat loss per temperature difference from the measured HSL slope. The resulting air change rate can then be compared to the prediction based on the airtightness test results and C.-Y. Shaw's correlation (Section 4.1.2). However, performing the subtraction shows that the initial assumption is significantly in error, confirming the overprediction problem discussed in Section 5.1.1. For more than half of the "measured" air change rates are negative. From this calculation we can thus say nothing about the accuracy of the air change rate predictions based on airtightness fan test results.

The comparison of those predictions with the results expected from the airsealing methods used and homeowner comments (Section 4.1.2) does suggest some serious difficulty in properly indicating the effects of airsealing retrofits. As discussed in Appendix D.2, the fan test indication of airtightness does not account for the distribution of leaks that is vital in defining the amount of natural air leakage through those leaks. And this distribution can be significantly altered by airsealing, so that the change in fan test result before and after upgrading may well not correspond to the reduction in air change rate occasioned by the retrofit work. Thus, fan tests alone cannot give the basis for a good air change rate correlation. The simplest indication of leak distribution with which to supplement the airtightness information is determination of the neutral pressure level of the house (that location in the height of the building at which natural forces driving air movement through the wall are zero) (23).

5.2 AIRSEALING EFFICACY

The measured results for the airsealing work (Sections 4.5.3 and 4.6.2) show great variability, especially in comparison with the roughly comparable levels of effort expended for contractor airsealing as indicated by the normalized costs (Section 2.3). There are two aspects of airsealing work that could explain this:

a) The difficulty in sealing a given leak. Applying sealants at the inner surface of the wall to seal a tortuous air path through the wall, which may also connect with many other paths, can present problems due to workmanship and also sheer physical impossibility.

b) The arbitrariness concerning which leaks are attempted to be sealed. The choice of leaks is defined by accessibility, ability to be effectively sealed, significant fan-induced air flow and standard ideas about which leak locations are important. Only the last of these (maybe) has any correlation with the ultimate purpose of airsealing, which is to block leaks through which infiltration or exfiltration is occurring. And sealing any given leak can change the distribution of leaks so that the natural air flow through any other hole can possibly change in a non-obvious way.

The next effect of this present state of the airsealing art is that expended effort and natural air change effect may bear little relationship to each other. Also, it is difficult to guarantee a minimum reduction in any given dwelling. This intrinsic variability is an impediment to third party (eg, utility) promotion of such work. Development of an air change rate test that is as straightforward as a fan test would allow airsealers to see the real effect of their work and iterate accordingly.

5.3 UPGRADING PROBLEMS

5.3.1 Workmanship, Materials

The inspections and homeowner comments were generally positive about the upgrading work done. A few problems (sealant odour, stuck doors, etc) were noted however. This could be expected for a labour-intensive process which requires much custom work and entails a significant (although short-term) disruption of someone's home. This relatively low-level risk needs to be taken into account if a utility is considering promoting such work.

5.3.2 Longer-Term Concerns

The major potential problem resulting from upgrading (especially airsealing) work concerns changes to the long-term indoor air quality, if compensations for the reduced natural ventilation are not made. From the comments made by the homeowners (Appendix E), almost all houses showed signs of being tighter (fewer drafts, increased window condensation, etc; houses 71-06 and 71-28 exhibited changes due more to insulating than airsealing; no comments were received from houses 71-15 and 71-34). Comments obtained at different times were somewhat contradictory in some cases, possibly indicating accommodation to new humidity and ventilation regimes. There are also indications of alterations to house operation and living habits (venting dryers outdoors, turning off humidifiers, airing the house, etc) to alleviate air quality or humidity situations. These instances of worsening indoor air quality are obviously related to the tightening of the envelope by airsealing. They may also be the result of the overall improvement of the envelope's thermal characteristic. This lowers the duty cycle of the furnace and thus of the circulating fan under similar climatic

conditions. Less air circulation may affect the distribution and mixing of fresh air throughout the house. Only one house (71-22) had a problem that required remedial action. (The addition of another adult in 1983/1984 may have contributed to the appearance of mold in the bathroom at that time; bathroom and kitchen fans were added in the fall of 1984.) In general, the levels of airsealing attained in this study did not significantly affect air quality, or could be accommodated with straightforward lifestyle changes or, in the limit, with the retrofit of a ventilating system.

From the point of view of an organization promoting upgrading work, one important question is whether one can ascertain at the time of upgrading if a problem may arise, so remedial measures could be instituted immediately. The obvious method of testing for this condition is a fan test, possibly augmented with an air-change-rate correlation. Comparison of reductions of relative ELAs (Appendix A, column 25) or predicted natural air change rates (column 27) with the comments in Appendix E gives an indication of the efficacy of such measures in anticipating trouble. For houses with evident tightening from the comments, one looks for significant reductions in the fan results; for humidity or air quality problems, one also looks for low absolute values for after-upgrading airtightness (below 2 cm^2/m^2) or natural air change rate (below 0.3 ac/h). Using these criteria, there is a correlation between testing and reality in 7 cases (houses 71-06, 71-12, 71-22, 71-26, 71-27, 71-32 and 71-33); there is none in 7 cases (houses 71-04, 71-07, 71-09, 71-10, 71-14, 71-25 and 71-28); two houses (71-15 and 71-34) have no homeowner comments for comparison. Although this record is none too good, the one significant problem house (71-22) was identified (although not strongly) by its fan test results.

Depending on fan tests to show underventilation situations may not be prudent at the present state-of-the-art. Work is proceeding else-

where (16) to refine a set of tests (tracer gas, air flows, backdraft potential, etc) to characterize the performance of ventilating systems; these more direct measures are probably better at discovering potential difficulties.

Only six houses had exhaust fans and in some of them the fans were unused. Even leaky houses which depend on natural ventilation have periods of low ventilation in mild, calm weather. Mechanical ventilation can ensure adequate fresh air in all circumstances. Thus it may be prudent when promoting airsealing retrofits to include provision for installing exhaust fans where they do not exist and to educate the homeowners to utilize them if problems appear.

5.4 LIFESTYLE CHANGES

As has been discussed in the previous section, many of the homeowners altered their living habits to accommodate the changes in their indoor environment caused by the upgradings. (We assume no lifestyle changes for reasons independent of the retrofits.) Many of these alterations have a direct impact on energy consumption and demand requirements: airing the house more, using exhaust fans more regularly, venting clothes dryers outside, stopping humidifier operation, decreasing the thermostat setting because of reduced drafts, deepening the night setback because the house cools off more slowly and recovers more quickly, etc. The energy and demand effects are intrinsically measured in this experiment, and are the likeliest reason for the inaccuracies seen in the reduction predictions (Sections 4.4.3, 4.5.4 and 4.6.2). It is significant that the errors on the energy side and thus the assumed lifestyle effects on energy consumption are larger than the demand errors and their presumed lifestyle causes. This suggests occupant activity changes vary with weather: for example, the house is aired

more than before upgrading in the shoulder seasons (spring and fall) but less so as it gets colder outside.

The first order indication of a lifestyle change is a thermostat setting alteration. The June 1983 survey question on significant household changes (No. 4, Appendix E.1) only implicitly asked for this information, and elicited none. The fact that indoor temperatures (which can be different than the thermostat setting) were not monitored in the dual energy field trial (our 'before' year) led us to continue not recording this data, nor explicitly asking for thermostat information until the Fall 1983 survey (see Table C.3). We thus have no indication of the occupants' response to their new thermal environment. Three scenarios are possible:

a) Thermostat settings are not changed. Temperatures and thus comfort levels are increased.

b) Thermostat settings are increased to result in similar energy bills and much increased comfort.

c) Thermostat settings are decreased to maintain similar comfort levels.

Responses intermediate to the three cases are also possible. (In a field trial situation when the occupants know they are being monitored for a reduction in energy consumption, it is even possible for them to go beyond c) and diminish their original comfort levels (the Hawthorne effect).) Cases a) and b) are often termed "buying comfort with energy savings". Realistically, such temperature changes probably don't go beyond a range from 18°C to 22°C. For average heating seasons inside-outside temperature differences of about 20°C, this suggests up to a 20% effect. This is magnified by the fuller utilization of free

internal gains which further reduce the space heating energy required from the furnace. Most of the upgradings in this test have predicted technical effects of the same size or smaller than this postulated lifestyle effect. The measured savings thus depend critically on which scenario any given homeowner actually follows. It is thus strongly recommended that similar field trials in the future monitor space temperatures (upstairs and basement) and occupant behaviour both before and after retrofit.

Human comfort depends on six factors (26):

1. Activity level
2. Clothing level
3. Air temperature
4. Mean radiant temperature
5. Relative humidity
6. Air movement

The first factor is a constant through a thermal envelope upgrading. The second can be altered in response to such a change. The two temperatures are affected directly by adding insulation, indirectly by cutting down drafts and altering the furnace oversizing, and also by resetting of the thermostat. The last two factors are indirectly affected by airsealing (high RH in a tighter house, fewer drafts) but can also be affected by the homeowner (more bathroom fan use, turning off the power humidifier, running the furnace fan continuously on low speed).

Incorporation of the comfort equations of reference 26 in a predictive model like HOTCAN could help to define the gross effect of lifestyle on consumption. For retrofit calculations, the model could allow user choice of the homeowner behaviour scenario discussed above, which would

illuminate the effect on the savings of the assumed lifestyle response to the thermal improvements.

5.4.1 Balance Point Temperature

The suggestion of a weather-dependent lifestyle effect in the last section leads naturally to a discussion of the change in balance point temperature observed on upgrading these houses. In this context, the balance point temperature is that outdoor temperature below which a house's heating system first begins to be required. The space heating needed above this temperature is supplied by "free" heat: solar gains, appliance waste heat, gains from occupants etc. The base temperature used to determine degree-days (18°C) is meant to correspond to an average balance point temperature, but it has recently been determined that for present-day house construction and appliance usage, 14°C is a better value (17). Any given house has an individual balance point temperature determined by the structure and the occupants' habits. The temperature intercept of the HSL line measured in this study is a direct determination of this quantity. Table 6 (and Appendix A, columns 47 to 49) lists these values both before and after upgrading.

The average before balance point temperature is the same as the value suggested in (17), this may be somewhat fortuitous because the absolute values of these temperatures are prone to error because of offsets between the local climate and the airport weather data used. But the remarkable result is the almost consistent increase (independent of any offset) in balance point temperature after upgrading. Increasing the thermal integrity of a residence is expected to decrease the HSL slope (a measure of the overall heat loss coefficient of the structure),

Table 6

BALANCE POINT TEMPERATURES

Category	House Number	Balance Point Temperature (°C) Before	After	Increase
DIY Seal	14	13.3	14.8	1.5
	26	11.3	13.7	2.4
Seal	22	13.9	15.2	1.3
	25	11.9	15.3	3.4
	27	11.3	13.5	2.2
	33	14.4	15.3	0.9
Seal & Basement	04	11.5	15.8	4.3
	09	13.1	14.3	1.2
	12	14.7	14.0	-0.7
	34	15.8	16.9	1.1
Basement	06	12.7	16.8	4.1
	10	16.7	14.8	-1.9
	15	13.0	12.7	-0.3
DIY Basement	07	18.1	18.8	0.7
Attic	28	13.1	13.9	0.8
Attic & DIY Seal	32	15.4	17.1	1.7
Average		13.8	15.2	1.4

decrease the design heat loss (the HSL demand intercept) and decrease the balance point temperature (free heat is more effectively utilized). The former two expectations are observed in our data (Appendix A, columns 42 and 46, respectively), but the latter is not. This effect has also been observed in a number of recent reports of upgrading field studies similar to this one (18,19,20). In all these cases, this phenomenon is termed an anomaly or not discussed explicitly, and assumptions are made to avoid the issue in analyzing the data. The quality of the data in this experiment and the existence of these other instances lead me to conclude that this balance point cross-over after

upgrading is a real effect which must be taken into account when determining the savings due to retrofit. No simple structure-based energy predictor (like HOTCAN) can do this job, only actual measurements as in this study. This phenomenon may be a significant part of the cause of HOTCAN's energy overprediction. Because the effect seems most likely to be based on occupant lifestyle changes, a proper prediction can only be developed with the help of sociologists, etc, and the taking of detailed occupant as well as structural data. Without going to this obvious complication, organizations sponsoring upgrading work are strongly urged to significantly discount energy savings estimated from simple physical models. The results of this, admittedly small, experiment suggest a discount factor of three on average, but a wide variation of this factor in individual cases.

5.5 COST-EFFECTIVENESS

The upgrading costs and energy and demand reductions seen in this experiment can be used, with certain assumptions, to give yearly net savings for the upgrading work performed. Table 7 (and Appendix A, columns 50 to 54) summarizes the results developed in Appendix H. The costs are spread out over an assumed life of 50 years for the upgrading work (similar to the life of the house itself) using a 3% real interest rate (ie, above inflation; this value is presently low, but historically appropriate). The homeowner savings were calculated using the Ontario 1982 average end rate of 3.58 ¢/kW·h. The electric utility designation in this case means the bulk generation and transmission of Ontario Hydro plus the distribution and direct billing of a typical municipal utility; this combination is equivalent to the electric utility in other provinces. Details of the calculation of the electric utility yearly net savings can be found in Appendix H. Although the detailed savings due to decreased demand and energy are those appropriate to Ontario, it

is expected that the overall result is similar to that which would be obtained using data for other utilities. The utility data is based on 1985 costs and has been discounted to 1982 using the ratio of residential end rates for those two years. The societal saving is the sum of the customer and utility savings.

A net societal saving occurs for 10 of the houses and for the overall average. It should be noted that the yearly costs, and thus net savings, are relatively sensitive to the economic parameters chosen. For example, assuming a 30 year life and a 4% rate would increase yearly costs 49% and change a net saving to a net cost for 4 houses. The technical reasons for specific instances of net cost have been discussed previously, to the extent that they can be clarified with the available information.

It must also be emphasized that not all costs or benefits can be quantified in the strict economic terms described above. For example, slight diminutions of indoor air quality might be tolerated without increasing ventilating, but represent a "health cost" of airsealing. On the other hand, decreases in cold drafts can make airsealing worthwhile even if energy savings do not fully cover the costs incurred. Similarly, insulating a basement can create usable living space at modest cost. As well, the capital cost of upgrading increases the house's asset value; this can be partially recovered on disposition. This capital cost can also be considered a premium for insurance against significantly escalating energy prices.

As is obvious, the exclusion of upgrading labour costs (ie, homeowner-performed work) tends to amplify the net savings. Section 2.3 shows that do-it-yourself costs are roughly one-third of the contractor costs for similar jobs. This suggest that utility-sponsored programs could key on the materials costs of upgrading work. Homeowner-done

insulation projects can be as effective as contractor work; this may be less true of airsealing jobs. Very roughly, the costs and savings for each category of upgrading track together. No firm conclusion can be drawn concerning the comparison between categories eg, whether airsealing is better than basement insulation.

Table 7

COSTS AND SAVINGS

		Yearly Costs and Savings (1982$)				
Category	House Number	Upgrade Costs	Homeowner Savings	Electric Utility Savings	Societal Savings	Net Savings
DIY Seal	14	$ 16	$ 43	$ 48	$ 91	$ 75
	26	4	-57	37	-20	-24
Seal	22	32	0	-21	-21	-53
	25	46	0	47	47	1
	27	22	54	22	76	54
	33	19	14	14	28	9
Seal & Basement	04	168	75	102	177	9
	09	105	68	94	162	57
	12	86	75	-5	70	-16
	34	78	90	11	101	23
Basement	06	86	0	-18	-18	-104
	10	60	36	-30	6	-54
	15	48	68	27	95	47
DIY Basement	07	26	64	13	77	51
Attic	28	57	75	28	103	46
Attic & DIY Seal	32	>10	-7	22	15	<5
Average		$ 54	$ 37	$ 25	$ 62	$ 8

From Table 7, it can be seen (by subtracting column 3 from column 4) that only six homeowners would see net dollar savings from the energy

savings due to the upgradings. The electric utility savings in most cases (on average, two-thirds the homeowner savings) helps create a net societal saving. When the contributions of energy and demand savings are isolated (see Table 8), Hydro's savings are seen to be due to the demand savings being over twice (on average) the energy penalty (due to the purely energy-based charge in the residential sector). Societally, energy and demand savings are both positive, and the demand savings are twice those for energy. It can be concluded that demand reductions due to thermal envelope upgradings are more important than energy savings, but that present consumer price signals via utility rates do not reflect this fact at all. This suggests that, under present residential pricing, there may need to be utility contributions toward the capital costs of upgrading if the full economic benefit of such work is to be obtained. It is worth reemphasizing here that planning any such utility involvement on the basis of predicted savings will lead to unwarranted optimism concerning potential savings, although demand predictions are significantly more accurate than those for consumption.

Table 8

AVERAGE ENERGY AND DEMAND SAVINGS (1982$)

Sector	Energy	Demand	Total
Homeowner	$ 37	$ 0	$37
Electric Utility	-19	44	25
Society	$ 18	$44	$62

5.5.1 Trade-Off with Service Entrance Upgrading Costs

It was suggested in the Introduction that homeowners converting to all-electric space heating might be able to trade off thermal upgrading

costs for service entrance upgrading costs. The average retrofit cost in this study ($1400) is roughly comparable to the cost of upgrading a service entrance to 200 A ($1000 to $1200). However, the conditions under which the trade-off might be made are somewhat restricted: ie, only if an "official" heat loss calculation is brought from above to below specific heating load break-points which are functions of service entrance capacity and control strategy, as shown in Table 9. (Other service sizes are much less common. This table doesn't cover heat pump loads.)

Table 9

RECOMMENDED LOAD LIMITS (27)

Service Size (A)	Uncontrolled Load (kW)	Instantaneous Load Controller on Dryer (kW)	Load Limiter Sensing Total Service Load (kW)
60	0	5	10
100	5	10	18

The houses tested in this experiment are roughly typical of Ontario homes (3, p 7). Only one of them has a calculated design heat loss close to the 18 kW break-point and two within 13% (the average demand reduction) of the 10 kW one. This gives an indication of the potential for the trade-off (more recent housing is larger, but better insulated, so the distribution of space heating demands is probably not changing significantly). The measured demand reductions show a standard deviation of 10% about the 13% average. With significant confidence (eg, over 90%), one cannot rely on obtaining a demand reduction. There is also the problem of whether demand reductions would appear in an "official" heat loss calculation (upon which decisions are made). For example, some existing calculation procedures do not make any provision

to vary the air change rate; thus airsealing effects would not be accounted for. In addition, there is some question about the reliability of 60 A and 100 A service entrances after the addition of electric heat (3, p 86). Also, comfort concerns may arise when the furnace is turned down to accommodate a load that doesn't contribute its waste heat to space heating (eg, the dryer or the water heater). All in all, it would seem inappropriate to suggest any significant potential for this trade-off.

5.6 ABILITY TO GENERALIZE

Three aspects of this field trial tend to lessen our ability to generalize from the results obtained. Firstly, the winter before upgrading was significantly colder than normal while the winter after was much milder than normal. Thus direct comparison of raw measured data was not appropriate, and a weighting based on standard degree-days was used to obtain comparable consumptions for normal weather. The vast majority of weather-based variations are taken care of by this stratagem. It was decided that the significantly greater effort to include other weather effects (wind, solar radiation, house-specific degree-day reference temperature, etc) was not justified by the modest extra accuracy that could be obtained. We are confident that the consumption reductions presented are a fair reflection of the effect of thermally upgrading these houses. Similarly, the small standard errors of the slopes of the heating system load lines obtained from the statistical analysis of the measured data prove the correctness of our demand reduction determinations.

Another difficulty is the modest number of houses studied in this experiment. As is evident from the data presented, there are numerous individualities of the houses, both thermally and in the way that they

were operated. (There is no economic possibility of doing this level of experiment in a sample of similar houses large enough for statistical validity. It is usually suggested that occupant lifestyle effects can be averaged out (within 5% with 95% confidence) if a sample of at least 40 nominally-identical dwellings is available (21); a more stringent requirement is probably needed where consumption, etc differences need to be determined.) On one level, then, we just have a set of 16 case studies. However, there are reasons to suggest that some generalizing is justified. Standard retrofitting materials and techniques and good workmanship were used in the upgradings. Groups of four houses with the same category of upgrading allow some averaging and comparison with other categories. And the full 16 houses show consistent results in some instances, albeit with some individual scatter. For example, the overpredicting of the consumption reductions is common to almost all the houses. Generalizing the results of this field test fundamentally boils down to making a judgement on the variability across the 16 houses studied of the result being explored. Some of these judgements are reflected in the conclusions drawn from this work; the readers of this report must make their own assessments of the validity of such judgements. It is likely that the qualitative conclusions drawn can be relied upon, but that the quantitative results should not be taken too far out of the specific context of this field trial.

The third problem in this experiment is the use of supplemental space heating devices even after careful screening of the participants and inclusion in the legal agreement with them of a clause prohibiting such use. The descriptions in Appendix B detail these situations to the extent that they were ascertainable. It is assumed that no significant change in house operation (eg, fireplace usage) occurred between 1981/1982 and 1982/1983 as a function of outdoor temperature, so that the relative changes due to the upgradings were determined correctly even if absolute demands or energy consumptions were not quite.

6 CONCLUSIONS

6.1 FROM THE FIELD TRIAL

1. Sixteen typical Ontario houses were thermally upgraded in various ways (homeowner and contractor-performed airsealing, basement and attic insulation) and were monitored before and after the change to obtain consumption and demand reductions, costs, and indications of any difficulties encountered. Data analysis was performed to eliminate gross effects of weather between the two years.

2. Space heating consumption reductions averaged 6% but ranged rather widely: from -11% to +15%; demand reductions averaged 13% (-6% to +30%). More extensive upgradings showed larger savings, on average. Explanations for the anomalous results are offered in the text.

3. Predictions of the expected reductions were made using HOTCAN and average measured air change rates. Consumption was 80% over-predicted on average; the percentage energy savings calculated were roughly three times larger than those measured. HOTCAN gave demands 40% too large, although the percentage power savings are comparable to those measured.

4. The airtightness measurements using fan depressurization, and the results of C.-Y. Shaw's correlation to give natural air change rates did not correspond well to the work done or the consumption reductions measured.

5. Only a few problems were encountered because of this upgrading work; they were not serious or were simply rectifiable.

6. Most upgradings showed net savings to society (homeowner plus electric utility).

7. Some of the anomalous results and the difficulty in predicting upgrading effects are ascribed to lifestyle causes. Such causes are also thought to account for the increase in balance point temperature after upgrading seen in this study.

6.2 FOR HOMEOWNERS, UTILITY ADVISORS

1. On average, more extensive thermal envelope upgradings give rise to larger energy savings. However, the effect on individual dwellings can be quite variable. It can even be negative, in rare cases, when lifestyle effects predominate. One cannot check for such savings without taking into account differences in energy cost and weather severity (via degree-days) between the "before" and "after" periods.

2. Existing methods for predicting energy reductions do not give good guidance. Extensive house data and occupant information are required, and even then the predictions of absolute consumptions and energy savings can be significantly in error.

3. Fan depressurization tests can give an indication of where leaks are and roughly how extensive they are. But fan tests alone (or with existing air change rate correlations) don't indicate how important a leak is for natural air change nor how effective airsealing has been in reducing natural air leakage nor whether natural infiltration is adequate for ventilation purposes.

4. Short-term household disruptions are a normal part of upgrading work. Workmanship problems and longer-term health concerns are not usual, and can be easily sorted out.

5. Energy savings alone do not necessarily cover the costs of upgrading. Comfort improvements and other less tangible benefits still can make such work worthwhile. Performance of the work by the occupants significantly reduces the first cost and increases the economic viability of the retrofit.

6. Electric utilities benefit significantly from the demand reductions resulting from upgradings, but present rate structures don't allow such benefits to be passed on to their customers.

7. How homeowners operate their house and what their attitudes are to energy usage make a significant difference to the extent of savings they will see from upgrading.

6.3 FOR RESEARCHERS

1. A sample of sixteen houses with various categories of upgradings does not allow quantitative conclusions that can be generalized, although many qualitative results can be obtained.

2. Detailed monitoring and occupant surveys are necessary to allow explanation of individual results. Extensive pre-planning, good co-ordination of the many people involved, good communication with the homeowners and support from local personnel of the testing agency are vital to carrying out such an experiment.

3. Standard degree-day normalization corrects for most of the effects on consumption of weather fluctuations.

4. Demand effects can be quantified closely using the heating system load line method of analysis described in this report. Hourly demand data are needed to accurately characterize a house's heat loss.

5. Simple energy predictors like HOTCAN don't seem to capture all the parameters necessary to properly quantify upgrading reductions; they also may deal inappropriately with certain components of heat loss.

6. See Section 6.2, No 3, re fan testing, etc.

7 RECOMMENDATIONS

7.1 FOR SPONSORS OF UPGRADING PROGRAMS

1. Electric utilities should consider promoting thermal envelope upgrading work if the significant demand consequences, found in this experiment, are useful to them because the present rate structure doesn't adequately reflect generation, transmission and distribution marginal costs.

2. In such programs, if predictions of the before-upgrade consumptions in individual cases are not close to the actual values using reasonable assumptions (based wherever possible on surveys or monitored data) then any predicted savings must be discounted.

3. Such programs can best deal with possible long-term effects of airsealing by promoting the installation and utilization of mechanical ventilation.

4. In support of such programs, the research into diagnostic techniques and the recommendations for demonstration projects described below may need to be sponsored.

7.2 FOR RESEARCHERS

1. Further development of HOTCAN or similar energy predictors should be undertaken to make them more useful in retrofit situations. More inputs defining occupant behaviour and the possible changes caused by upgrading need to be considered. Areas of possible technical inadequacy have also been discussed in the text, including the lack of an infiltration model based on readily available house data. The detailed data from this field trial are available to prove such modifications.

2. Development of a straightforward test (possibly an extension of fan depressurization) to quickly indicate the effect of airsealing on natural air change rate is needed. Also, further development of diagnostics to test for the potential for ventilation-related problems would be useful.

3. A larger sample, randomly selected but matched to typical construction and demographics, and with a control group (possibly two groups: directly monitored and blind-monitored via utility bills), would allow generalization of quantitative conclusions.

4. An all-electric space heating sample of houses would simplify the analysis of an upgrading experiment and yield direct measures of coincident demand effects.

5. Detailed monitoring of interior space temperatures would aid understanding the upgrading results and improve the accuracy of predictions.

6. Because of general societal trends in conservation, and the disturbance to natural occupant behaviour caused by detailed monitoring and questionnaires, a long-term field trial is suggested. More than one year of "before" monitoring allows an indication of trends, and continued measurements after the retrofits can show if altered behaviour is long- or short-lived. Two years before and three after are proposed. Use of simple billing data for even longer periods, suitably weather-normalized, would further confirm the results.

7. To understand individual results, extensive monitoring and collection of house and occupant data must be done, as detailed throughout this report.

8. Rates researchers might consider the implications of this work on the design of residential space heating rate structures.

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APPENDIX

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